Influence of Augmented Feedback on Coordination Strategies

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ABSTRACT. The authors examined the influence of knowledge of results (KR) and concurrent feedback (ConFB) on coordination strategies in learning a 2-finger discrete force-production task. In Experiment 1, 4 groups learned the task under the following feedback regimes: ConFB, ConFB with knowledge of no-KR test (ConFB test information), KR after every trial (100% KR), and KR after every alternate trial (50% KR). Results show that the ConFB group had lower errors during acquisition but the highest errors in the no-KR transfer test. An uncontrolled manifold analysis showed that participants in the ConFB group adopted a strategy that tended to use multiple solutions to achieve the goal during acquisition, although they could not retain this strategy in the no-KR test. Both KR groups retained the same coordination strategy from acquisition into the transfer test, even though this strategy was not conducive to producing a constant force. These results show that ConFB facilitates using different solutions from trial to trial to achieve the same goal, and this may be a reason for poor performance when feedback is removed.

Keywords: concurrent feedback, guidance hypothesis, knowledge of results, motor variability, redundancy, uncontrolled manifold

From theoretical and applied perspectives, one of the major issues of interest in motor skill acquisition is how information feedback influences learning (for reviews, see Adams, 1987; Newell, 1976; Salmoni et al., 1996; Wulf & Shea, 2004). Probably the most common type of augmented information that researchers have studied is knowledge of results (KR), terminal information that is provided about the outcome of the movement in terms of the task goal (Annett, 1969; Schmidt & Lee, 1999).

Early research on KR espoused the view that KR was essential for learning (Thornike, 1931). Though this position was eventually challenged (e.g., Seashore & Bavelas, 1941), KR has continued to play a pivotal role in theories of motor learning. For example, in a closed-loop theory of motor learning, Adams (1971) emphasized the role of KR in strengthening the perceptual and memory traces. In general, experiments showed that improvements in performance were rapid in the presence of KR and that a greater amount of practice with KR enabled stronger retention even when KR was removed (e.g., Newell, 1974).

Salmoni et al. (1984) proposed a guidance hypothesis for KR (see also Annett, 1969) that was based in part on the distinction between learning and performance. The guidance hypothesis holds that KR guides the performer toward the goal, resulting in good performance during acquisition, although that performance deteriorates significantly once KR is no longer available. An analogy that is used often is that KR acts like a crutch, enhancing performance when it is present, but that excessive reliance on KR hampers performance once it is removed (Schmidt & Lee, 1999). The guidance hypothesis has been tested in several ways: changing the relative frequency of KR (e.g., Wulf & Schmidt, 1990), delaying KR (e.g., Lavery & Suddon, 1962), providing summary KR (Salmoni et al.), and comparing the effects of KR and guidance (Lee, White, & Carnahan, 1990). In general, the results have provided support for the guidance hypothesis (for reviews, see Schmidt, 1991; Swinnen, 1996; Wulf & Shea, 2004).

Researchers have also observed the guidance effect with concurrent feedback (ConFB; i.e., information about performance that is given during performance; e.g., Schmidt & Wulf, 1997; Vander Linden et al., 1992). Using an isometric force production task, Vander Linden et al. showed that practicing with ConFB causes a greater decrement in performance in a no-KR test compared with practicing with KR. Similarly, in a series of experiments investigating manual-aiming tasks, Proteau (1992) and Proteau et al. (1993) have shown that a group that had vision of the hand during reaching (i.e., ConFB) had greater errors when transferred to a no-KR condition compared with a group that saw only the target (i.e., KR). Researchers have proposed that ConFB may have stronger guidance properties than KR because it provides more direct information about achieving the task goal (Lai & Shea, 1999).

Hypotheses on the mechanisms underlying the guidance effect can be grouped into (a) an information-processing perspective or (b) a movement variability perspective. From an information-processing perspective, one hypothesis is that learners become too dependent on augmented feedback during acquisition and may not process information from intrinsic sources of the task that are critical to be able to perform the task without KR (Salmoni et al., 1984; Schmidt, 1991). Several studies have shown support for this hypothesis; for example, Swinnen et al. (1996) showed that instantaneous KR (i.e., providing KR immediately after the movement) degrades learning because it may block information processing. Also,
Anderson, Magill, Sekiya, and Ryan (2005) showed that participants in an instantaneous KR group reported using fewer information sources of intrinsic feedback (through a self-reported questionnaire) compared with a group that received delayed KR. Similarly, when researchers informed participants in advance that they would be tested on a no-KR test, participants performed better than when they were not told about the test, presumably because knowledge of the no-KR test directed their attention toward intrinsic information sources in the task (Laverty, 1962). An alternative information-processing account of the decrement in performance once augmented feedback is removed is the specificity of practice hypothesis (for a review, see Proteau, 1992). The specificity of practice hypothesis proposes that learning involves integrating all relevant sources of information available into a sensorimotor representation. Augmented feedback that is provided during acquisition becomes part of this sensorimotor representation, and its removal, therefore, results in a large decrement in performance. There has also been some support for a related prediction of this hypothesis that a greater amount of practice with augmented feedback results in larger errors when the feedback is removed (e.g., Proteau, Marteniuk, & Lévesque, 1992).

The focus of the present article is from a second—but related—perspective that links the dependence on augmented feedback with movement variability. The hypothesis is that dependence on augmented feedback causes maladaptive corrections from trial to trial for errors that are within the limits of motor variability (Schmidt, 1991). Therefore, these corrections may be detrimental to movement consistency (Bilodeau, 1966; Sherwood, 1988). In contrast, in conditions in which the dependence on augmented feedback is reduced, there is more stable trial-to-trial behavior, resulting in better retention. Support for this hypothesis has been mixed and generally tested by presenting KR immediately after the trial or delaying it until the end of the subsequent trial. Sherwood showed that the variable errors (VEs) were lower in the group that received delayed KR compared with the group that received KR immediately. In contrast, Anderson, Magill, and Sekiya (1994) showed the opposite trend in which VEs of the group that received KR instantaneously were smaller than the delayed KR group during acquisition and the transfer test. Schmidt and Wulf (1997) also suggested that ConFB causes greater variability in the spatiotemporal pattern produced in achieving the task goal compared with the variability that the KR group causes.

In considering the movement variability hypothesis, it is important to note that most of the aforementioned studies have used variability of the outcome as an index of movement variability. An important issue in this regard is whether the movement variability is examined at the level of the outcome or the level of individual effector degrees of freedom. Bernstein (1967) emphasized this distinction by using the term “repetition without repetition” (p. 134), indicating how a particular task outcome could be achieved repeatedly without repeating the same movement pattern. This is because the redundancy present at different levels in the motor system (e.g., joints, muscles, motor units) precludes a direct relation between outcome and movement variability. This effectively means that participants may be able to produce the same outcome (which would lead to low VE) even when using different movements from trial to trial (high movement variability).

**EXPERIMENT 1**

In the present study, we investigated the influence of augmented information on task outcome variability and movement variability. We examined four groups under different augmented feedback schedules (two groups with ConFB, two groups with KR). To analyze the distinction between variability at the level of task outcome and at the individual degrees of freedom, we used a task involving two degrees of freedom. The task was to produce a discrete pulse with a peak total force of 10 N using the two index fingers. This task is redundant because a number of combinations of the two finger forces could be used to generate the same peak total force of 10 N.

We used the uncontrolled manifold (UCM) technique (Latah, Scholz, & Schöner, 2002; Schöner, 1995; Scholz & Schöner, 1999) to analyze the structure of variability across trials (see also goal-equivalent manifold in Cusumano & Cesari, 2006). The UCM analysis essentially partitions total movement variability into the following two components: (a) one component of variability that is goal-equivalent, in which the variations in the individual degrees of freedom result in the same task outcome (i.e., variability along the UCM) and (b) a second component of variability in which the variations in the degrees of freedom result in a change in the task outcome (i.e., variability orthogonal to the UCM). By comparing these two components of variability, the UCM analysis affords a quantification of different movement strategies underlying performance (Latash et al.). The UCM analysis is explained in greater detail in the Data Analysis section.

The issue of interest in the present study was how the variance in the two directions would change as a function of the different augmented feedback conditions. If augmented feedback caused variations in the individual degrees of freedom from trial to trial while still achieving the goal, we expected that there would be greater variance along the UCM and less variance orthogonal to the UCM. A second issue of interest was to compare the differences in coordination strategies between the acquisition blocks (when feedback is present) and the no-KR transfer test for the four groups. This would reveal the persistence of the coordination pattern that was learned during acquisition under the different augmented information conditions.

**Method**

**Participants**

Participants were 24 healthy volunteers (12 men, 12 women; $M_{age} = 27$ years, $SD = 6$ years). They were
randomly assigned into one of four groups (in each group, \( n = 6 \)) with the constraint that the number of men and women were equal in each group. All participants were right-hand dominant. Informed consent was obtained from participants, and the Institutional Review Board at The Pennsylvania State University approved all procedures.

**Apparatus**

We used two unidirectional load cells (Entran Devices Inc., Fairfield, NJ) that were placed on a 2.5-cm high wooden board to measure the finger forces. The two load cells were 11 cm apart and sampled at a frequency of 140 Hz. After amplification (Coulbourn Instruments, Model S72-25, Coulbourn Instruments, Whitehall, PA), we stored the signals on a computer using a 16-bit A/D converter. A 14-in. (35.6 cm) computer monitor located approximately 70 cm in front of the participant provided visual feedback. The target force level was centered on the screen, and the visual gain was set at 33 pixels/N.

**Procedure**

Participants sat facing the display, and we instructed them to rest their wrists on the table and place the index finger of each hand on a separate load cell. We also asked participants to keep their palms on the edge of the wooden board and exert force only with the fingers. Under this instruction, the metacarpophalangeal and the interphalangeal joints of the fingers were in slight flexion.

The task was to produce a discrete pulse using both index fingers, such that the peak value of the sum of the two forces was 10 N. Each trial started with an audible beep after which the participant would produce a pulse of force isometrically using the two index fingers. Though there was no explicit constraint on the time required to achieve the peak total force, we instructed participants to produce a smooth increase in force to the target force level. After each trial, we asked participants to lift their fingers completely off the load cells. During this period, the program reset the load cells to zero to offset the load cell drift. After the program reset the load cells, there was an audible beep after which the participant could produce the next pulse.

**Acquisition Blocks**

There were four independent groups that received different information feedback. In all four groups, the target line of 10 N was centered on the display. In the ConFB group, participants saw a vertical bar on the screen in which the instantaneous height of the bar from the bottom of the screen corresponded to the instantaneous total force being exerted, so that when the top of the bar touched the target line, the participants knew that they had produced a 10-N peak force. At the end of each trial, participants received KR about the peak force from (a) a horizontal line at the maximum height of the bar that indicated the peak force produced and (b) a text display of the peak force with 2-decimal precision. In the ConFB with knowledge of the no-KR test group (ConFB test information), we gave participants the same feedback as the ConFB group, except that they were told prior to the first block of acquisition that they would need to perform the same task under no-KR at the end of eight blocks. In the 100% KR group, the participants did not receive any feedback while they produced the pulse, but at the end of each trial they received the same KR as the ConFB and ConFB test information groups. Last, in the 50% KR group, the participants received KR as in the other three groups, but only after every alternate trial. On the remaining trials, we did not provide any information and still instructed participants to produce a pulse to match the criterion force. Each practice block consisted of 60 trials, and all participants performed eight blocks.

**No-KR Transfer Test**

After the eight blocks of acquisition, there was an immediate no-KR transfer test (2 min after the end of the last acquisition block) for all the groups in which the participants only saw the target force line and did not receive any augmented feedback after each trial. Participants performed one block of 60 trials in this condition, and we instructed them to match the same criterion force (10 N) that they had practiced. Except for the ConFB test information group, none of the other three groups were aware of the no-KR transfer test prior to the test.

**Data Analysis**

We discarded trials in which the participant started pressing on the load cells before the beep (i.e., before the load cells were reset to zero) from the analysis. The total percentage of such trials was less than 2%.

**Task Performance**

The performance of the participants in the acquisition blocks and the transfer test with respect to the criterion force was quantified using absolute constant error (ACE) for each block. We computed ACE by averaging the CE across trials in a block and then computing its absolute value. Also, we computed the VE as the standard deviation of the CE across trials in a block.

**Between-Trial Correlation**

To determine the structure of motor variability across trials, we computed a between-trial correlation. For each trial, the finger forces exerted by the right index finger \( F_{IR} \) and the left index finger \( F_{IL} \) were extracted at the instant of peak total force. Each trial can then be represented as a single point on the \( F_{IR} \) versus \( F_{IL} \) plot (see Figure 1). We used this procedure for all trials and computed the correlation of the distribution of points \( (F_{IR}, F_{IL}) \). This is a between-trial correlation because each point in the distribution is from a different trial. It is important to note that this is different from a within-trial correlation, which is the correlation of finger forces on a particular trial (for further details on the distinction between
between trial and within trial correlations, see Ranganathan & Newell, 2008). Because correlations are influenced easily by extreme values, we removed the outliers that fell outside the 97.5% confidence interval. We computed the Mahalanobis distance for each point from the center of the data cloud, and points for which the Mahalanobis distance was greater than a specified threshold value (corresponding to the 97.5% tolerance ellipse) were deemed outliers (Rousseeuw & Van Zomeren, 1990).

UCM Analysis

We used the UCM analysis to partition the variance across trials into the two following components: (a) variance along the UCM (VUCM) and (b) variance orthogonal to the UCM (VORT). Similar to the between trial correlation, the finger forces at the instant of peak total force, F_R and F_L, were extracted for each trial. In this task, the UCM is the line F_R + F_L = 10. Any variance along this dimension does not affect the total force. The line orthogonal to the UCM is the line F_R = F_L. Any variance along this line leads to a change in the total force. This distribution of points (F_R, F_L) is then projected on to the UCM dimension and the orthogonal dimension using the dot product. The variance of these projections yields VUCM and VORT, respectively (see Figure 1).

From the UCM analysis, we computed the total movement variance as var(F_R) + var(F_L), which is equivalent to VUCM + VORT, for each block. We quantified the amount of goal equivalent variance relative to the total variance using the goal equivalent variance fraction, which we computed as VUCM / (VUCM + VORT).

Correlation Between Error and Corrections

To investigate how the participants changed the individual finger forces in response to an error after they had learned the task, we calculated a correlation between the error on a given trial and the changes in the individual finger force on the next trial in the final block of practice (Block 8). In other words, if the task error on Trial n is expressed as E(n), then E(n) was correlated separately with the change in the finger forces, F_R(n + 1) – F_R(n) and F_L(n + 1) – F_L(n).

Statistical Analysis

For the acquisition blocks, we analyzed all dependent variables using an 8 × 4 (Block × Group) analysis of variance (ANOVA) with the within-participant factor being Blocks 1–8 and the between-participant factor being the four groups (ConFB, ConFB test information, 100% KR, 50% KR). For the no-KR transfer test, we used a one-way ANOVA for all the dependent variables to determine differences between the four groups.

We performed all statistical tests at a significance level of .05 and corrected violations of sphericity using the Greenhouse–Geisser correction. We performed hoc comparisons for the between-participant measure using Tukey’s HSD procedure, whereas we made the comparisons for the within-participant factor (block) using the Bonferroni correction. To limit the number of pairwise comparisons on the within-participant factor, we compared only Blocks 1, 4, and 8 in the post hoc analysis.

Results

Task Performance

| CE |

For the acquisition blocks, our analysis of |CE| showed a significant main effect for block, F(1.7, 34.3) = 5.04, p = .016 (see Figure 2). Post hoc comparisons among Blocks 1, 4, and 8 indicated that Block 1 had significantly higher |CE| compared with Blocks 4 and 8 (ps < .05). In general, participants tended on average to marginally overshoot the 10-N force level. There was not a significant main effect for group. For the no-KR transfer test, the analysis showed a significant main effect of group, F(3, 20) = 4.28, p = .017. Post hoc comparisons revealed that the ConFB group had significantly higher |CE| compared with the other three groups. Again, participants tended to overshoot the target force level on the no-KR test.
Influence of Augmented Feedback

VE

For the acquisition blocks, our analysis of VE showed a significant main effect for block, $F(1.4, 4.7) = 12.51$, $p < .001$ (see Figure 3). Post hoc comparisons among Blocks 1, 4, and 8 indicated that Block 1 had significantly higher VE compared with Blocks 4 and 8 ($p < .05$). There was also a significant effect of group, $F(3, 20) = 18.09$, $p < .001$. Post hoc comparisons showed that the 100% and 50% KR groups had significantly higher VEs than did the ConFB and ConFB test information groups. On the no-KR transfer test, the analysis revealed a significant main effect of group, $F(3, 20) = 4.36$, $p = .016$. Post hoc comparisons showed that the ConFB group had higher VE than did the 100% KR and 50% KR groups.

Total Movement Variance

The ANOVA for the acquisition blocks revealed a significant main effect of block, $F(2.2, 28.5) = 9.91$, $p < .001$. Post hoc comparisons showed that the total movement variance was higher in Block 1 compared with Blocks 4 and 8. There was also a significant main effect of group, $F(3, 20) = 11.54$, $p < .001$. Post hoc comparisons showed that the ConFB group had significantly lower variance than did the 100% KR and 50% KR groups. Also, the ConFB test information group had a lower variance than did the 50% KR group. For the no-KR transfer test, there was no significant difference in the between-trial correlation between the groups ($p > .05$).

Goal-Equivalent Variance Fraction (GEVF)

The GEVF showed the same trend as the between-trial correlation. For the acquisition blocks, the analysis revealed a significant main effect of group, $F(3, 20) = 17.26$, $p < .001$. Post hoc comparisons showed that the ConFB group had the highest GEVF compared with all the other groups. The ConFB test information group also had a higher GEVF than did the 50% KR group. For the no-KR transfer test, there was no significant difference between the groups ($p > .05$).

Correlations Between Error and Corrections

Table 1 shows the mean correlations between error and corrections of the two fingers as a function of group. Before running the ANOVA, the correlations in Block 8 for the four groups were first transformed to Z scores to satisfy the normality assumption. For both fingers, there was a significant main effect of group: for $F_R$, $F(3, 20) = 6.59$, $p = .003$; for $F_L$, $F(3, 20) = 10.47$, $p < .001$.
FIGURE 3. Mean variable error (VE) for the four groups across eight blocks of acquisition and the no-KR test.

FIGURE 4. Mean between-trial correlation of $F_L$ and $F_R$ across eight blocks of acquisition and the no-KR test. The correlations were averaged using Z scores and then back-transformed. $F_L$ = left index finger; $F_R$ = right index finger.
Negative correlations indicated that a positive error (i.e., overshooting the force level) was associated with a decrease in the individual finger forces on the next trial. Post hoc comparisons showed that the ConFB group had the weakest correlation compared with all the other three groups \( (p < .05) \). The correlations in the other three groups were not significantly different from each other.

**Time-to-Peak Force**

In Experiment 1, participants were not constrained to produce the pulse in a given time. We calculated the time-to-peak force as the time between pulse initiation—defined as the instant when the total force crossed 1 N—and the time at which the peak total force was reached. Table 2 shows the mean time-to-peak force during the acquisition blocks and the no-KR block for the different groups. During acquisition, the analysis showed that there was a significant main effect of group, \( F(3, 20) = 9.69, p < .001 \), in which the ConFB group had longer times-to-peak force than did the 100% KR and 50% KR groups \( (p < .05) \). During the no-KR transfer test, there was a significant effect of group, \( F(3, 20) = 3.46, p = .036 \), in which the ConFB group had significantly longer times-to-peak force than did the 50% KR group \( (p < .05) \).

**EXPERIMENT 2**

To investigate if the differences in motor strategies observed in Experiment 1 were simply a consequence of choosing different times-to-peak force, we reexamined two of the four groups that were widely different in terms of pulse time: ConFB and 100% KR. In this experiment, the time-to-peak force was constrained to 600 ms. We also included a second no-KR transfer test 24-hr after practice to examine if the trends seen in the 2-min transfer test were only transient.

### TABLE 1. Mean Correlations Between Error in Total Force on Trial \( N \), \( E(n) \), and Changes in Finger Forces on the Next Trial of Right (\( F_R \)) and Left (\( F_L \)) Index Fingers as a Function of Group

<table>
<thead>
<tr>
<th>Group</th>
<th>Correlation between ( E(n) ) and ( F_R(n+1) - F_R(n) )</th>
<th>Correlation between ( E(n) ) and ( F_L(n+1) - F_L(n) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ConFB</td>
<td>-.41</td>
<td>-.38</td>
</tr>
<tr>
<td>ConFB test information</td>
<td>-.66</td>
<td>-.62</td>
</tr>
<tr>
<td>100% KR</td>
<td>-.60</td>
<td>-.56</td>
</tr>
<tr>
<td>50% KR</td>
<td>-.63</td>
<td>-.65</td>
</tr>
</tbody>
</table>

*Note.* Correlations were computed in the last block of acquisition (Block 8). ConFB = concurrent feedback; ConFB test information = ConFB with knowledge of no-KR test; 100% KR = knowledge of results after every trial; 50% KR = knowledge of results after every alternate trial.

### TABLE 2. Means and Standard Deviations for Time-to-Peak Force for the Different Groups (in ms) in Experiments 1 and 2

<table>
<thead>
<tr>
<th>Group</th>
<th>Experiment 1</th>
<th></th>
<th>Experiment 2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Acquisition</td>
<td>No-KR test</td>
<td>Acquisition</td>
<td>No-KR test</td>
</tr>
<tr>
<td></td>
<td>( M )</td>
<td>( SD )</td>
<td>( M )</td>
<td>( SD )</td>
</tr>
<tr>
<td>ConFB</td>
<td>1,001</td>
<td>437</td>
<td>671</td>
<td>102</td>
</tr>
<tr>
<td>ConFB test information</td>
<td>610</td>
<td>386</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>100% KR</td>
<td>270</td>
<td>160</td>
<td>553</td>
<td>82</td>
</tr>
<tr>
<td>50% KR</td>
<td>264</td>
<td>136</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

*Note.* Experiment 2 used only two of the four groups in Experiment 1. Data from both no-KR tests were combined for Experiment 2. ConFB = concurrent feedback; ConFB test information = ConFB with knowledge of no-KR test; 100% KR = knowledge of results after every trial; 50% KR = knowledge of results after every alternate trial.
Method

Participants

Participants were 12 healthy volunteers (6 men, 6 women; M age = 28 years, SD = 5 years). They were randomly assigned into one of two groups (for each group, n = 6) with the constraint that the number of men and women were equal in each group. All participants except 1 were right-hand dominant. Informed consent was obtained from participants, and the Institutional Review Board at The Pennsylvania State University approved all procedures. None of the participants used in Experiment 1 were part of Experiment 2.

Procedure

The procedure was identical to that in Experiment 1 except that there was a time constraint on the time-to-peak force. We only tested two groups, ConFB and 100% KR, on this experiment. Neither group had knowledge of the no-KR transfer test. We gave the participants bandwidth feedback on the time-to-peak force (similar to that used by Mackrous & Proteau, 2007). The target time-to-peak force was set at 600 ms, with a bandwidth of 150 ms on either side. Therefore, when the time-to-peak force was smaller than 450 ms, the participant heard a low-pitched beep, and when the time-to-peak force was greater than 750 ms, the participant heard a high-pitched beep. Participants were reminded that the primary goal of the task was to be as accurate as possible in producing a peak force of 10 N.

Data Analysis

All data analyses were identical to those in Experiment 1. We also included trials that were outside the bandwidth region in terms of time-to-peak force in our analysis.

Statistical Analysis

For the acquisition blocks, we analyzed all dependent variables using an 8 × 2 (Block × Group) ANOVA with the within-participant factor being Blocks 1–8 and the between-participant factor being the two groups (ConFB, 100% KR). For the no-KR transfer tests, we analyzed all dependent variables using a 2 × 2 (Delay × Group) ANOVA with delay (2 min, 24 hr) as the within-participant factor and group (ConFB, 100% KR) as the between-participant factor.

We performed all statistical tests at a significance level of .05 and corrected violations of sphericity using the Greenhouse–Geisser correction. We performed post hoc comparisons for the within-participant factor using the Bonferroni correction. To limit the number of pairwise comparisons on the within-participant factor, we only compared Blocks 1, 4, and 8 in the post hoc analysis.

Results

Time-to-Peak Force

Table 2 shows the time-to-peak force for the two groups in Experiment 2. The difference in mean times-to-peak force between the two groups during the acquisition blocks was significant, F(1, 10) = 9.98, p = .01, with the ConFB group (M = 671 ms, SD = 102 ms) having longer time-to-peak force than the 100% KR group (M = 553 ms, SD = 82 ms). However, compared with Experiment 1, the two groups were much closer in terms of time-to-peak force. The difference between the groups was not significant during the no-KR transfer tests. However, as the standard deviations in Table 2 show, there was large variability in the ConFB group in the mean time-to-peak force. This issue is addressed further in the Normalized Distance From Criterion section.

Task Performance

Total Movement Variance

The ANOVA for the acquisition blocks revealed a significant main effect for group, F(1, 11.9) = 6.55, p = .021. There was also a significant main effect for group, F(3, 20) = 11.54, p < .001, with the ConFB group having a lower movement variance than the 100% KR group. The ANOVA for the no-KR transfer tests revealed significant group and block effects, F(1, 10) = 34.43, p < .001, and F(1, 10) = 5.36, p = .043, respectively. The interaction between group and block was also significant, F(1, 10) = 11.54, p = .002.
KR group. There was also a significant Group × Block interaction, $F(1.2, 11.9) = 4.71, p = .046$. Similar to the VE, the difference between the groups in Block 1 was larger compared with the rest of the blocks. For the no-KR transfer tests, the analysis indicated a significant main effect for delay, $F(1, 10) = 6.029, p = .034$, with a smaller total movement variance at the 2-min delay. When analyzing the difference between the groups, the 100% KR group had a significantly smaller variance than did the ConFB group at the 2-min transfer test ($p = .011$) but not at the 24-hr transfer test ($p = .375$).

**Between-Trial Correlation**

For the acquisition blocks, the analysis revealed a significant main effect for block, $F(3.4, 34.0) = 6.14, p < .001$. Correlations were higher in Block 1 compared with Blocks 4 and 8 ($ps < .05$; see Figure 5C). There was also a significant main effect for group, $F(1,10) = 166.66, p < .001$. Correlations in the 100% KR group were positive ($Mr = .64$), whereas the correlations in the ConFB group were negative ($Mr = -.34$). For the no-KR transfer tests, there was no significant effect of group or delay ($Mr = .65$).

**GEVF**

For the acquisition blocks, the analysis of the GEVF revealed a significant main effect for block, $F(2.9, 29.5) = 5.56, p = .004$. GEVF in Block 1 was significantly lower than in Blocks 4 and 8. There was also a significant main effect for group, $F(1,10) = 223.76, p < .001$, with the ConFB group ($MGEVF = .66$) having a higher GEVF compared with the 100% KR group ($MGEVF = .22$). For the no-KR transfer tests, there was no effect of group or delay ($MGEVF = .21$).

**FIGURE 5.** Mean dependent variables across eight blocks of acquisition and the no-KR tests for the two groups in Experiment 2. (A) Mean absolute constant error ($|CE|$). The scale on the y axis for the acquisition blocks is different from the no-KR tests. (B) Mean variable error (VE). (C) Mean between-trial correlation of $F_L$ and $F_R$. Correlations were averaged using $Z$ scores and then back-transformed. ConFB = concurrent feedback; KR = knowledge of results. $F_L$ = left index finger; $F_R$ = right index finger.
Between-Trial Correlations During the Pulse

In Experiment 2, because the times-to-peak force were similar between groups, we compared the between-trial correlations at different time instants along the trajectory of the force pulse (in addition to the instant of peak force reported previously). We computed this during the last block of practice (Block 8). Each force pulse (starting from initiation until the instant of peak total force) was split into time instants in increments of 10%. At each of these time instants, we computed the between-trial correlations between the finger forces. The analysis showed a significant main effect for time instant, $F(2.6, 26.1) = 20.99, p < .001$, and a significant main effect for group, $F(1, 10) = 13.88, p = .004$, which was mediated by a Time Instant × Group interaction, $F(2.6, 26.1) = 24.63, p < .001$. Pairwise comparisons using Fisher’s LSD between the groups at each time instant showed that the correlations between the groups were significantly different after the time instant, corresponding to the 50% of the pulse duration ($p < .05$; see Figure 6).

Normalized Distance From Criterion

The results from the 24-hr no-KR test did not show significant differences between groups in terms of task performance. However, given the high variability in the times-to-peak force, we examined the CE along with the time-to-peak force to investigate whether participants were guessing the force level (see Figure 7). The ideal performance according to the task goal was a CE of 0 N and a pulse time of 600 ms. We computed a normalized distance that indicated how far each participant was with respect to this criterion point (600, 0) using the formula $d = \sqrt{((T-600) / \sigma_T)^2 + (CE / \sigma_{CE})^2}$ in which $\sigma_T$ is the standard deviation of the time-to-peak force and $\sigma_{CE}$ is the standard deviation of the CE across all participants (both groups included) in that particular block. Because $\sigma_T$ and $\sigma_{CE}$ change from block to block, we performed pairwise comparisons between the two groups at three blocks: the last block of acquisition, the 2-min no-KR test, and the 24-hr no-KR test. The analysis revealed that although the groups were not significantly different at the end of acquisition, $t(10) = -.59, p = .564$, the 100% KR group was closer to the criterion performance in the 2-min test, $t(10) = 4.03, p = .002$, and in the 24-hr test, $t(10) = 3.02, p = .013$. This is also evident in Figure 7, which shows that the participants in the 100% KR group were both tightly clustered and closer to criterion performance in both no-KR tests, whereas there is a large variability in the performance of the ConFB group, indicating that the participants in the ConFB group were probably guessing the force level.

![FIGURE 6. Mean between-trial correlation of $F_R$ and $F_L$ at different times along the pulse in the last block of acquisition (Block 8) in Experiment 2. Correlations were averaged using Z scores and then back-transformed. ConFB = concurrent feedback; KR = knowledge of results. $F_L =$ left index finger; $F_R =$ right index finger.](image-url)
Summary

Experiment 2 attempted to control for differences in the time-to-peak force between the groups. This difference in time-to-peak force between the groups was reduced to approximately 118 ms in Experiment 2 compared with 731 ms in Experiment 1. However, the results from Experiment 2 were nearly identical to those in Experiment 1, both during acquisition and in the 2-min no-KR transfer test. The results of the 24-hr no-KR transfer test also revealed that although the 100% KR group showed a systematic drift from the 2-min to the 24-hr transfer test, they were closer to the criterion performance than were participants in the ConFB group, who seemed to be essentially guessing the force level at the 24-hr transfer test. These data are in accordance with previous studies (Park, Shea, & Wright, 2000; Vander Linden et al., 1993), which show that the effects of ConFB persist both in short- and long-term transfer tests.

GENERAL DISCUSSION

The purpose of the present study was to examine the influence of different types of augmented information on learning a redundant task with two degrees of freedom. Of particular interest was the examination of the difference in variability at the level of the outcome and the level of the individual degrees of freedom. In terms of force sharing between the fingers, the index finger of the dominant hand produced approximately 55% of the total force at the instant of the peak total force. The |CE| results were consistent with previous studies that showed that practicing with concurrent feedback leads to poorer performance on a no-KR test compared with practicing with KR information (e.g., Park et al., 2000; Proteau, 1992; Schmidt & Wulf, 1997; Vander Linden et al., 1993).

Similarly, in terms of VE and total movement variance, the ConFB group had the lowest variance during acquisition but had the highest variance in the no-KR transfer test.

However, when we partitioned the total variance and analyzed the variance along the UCM direction as a percentage of the total variance, the ConFB group had the maximum percentage of goal-equivalent variability during acquisition compared with all the other groups. This indicated that there was a tendency in the ConFB group toward using different goal-equivalent solutions from trial to trial. In the 100% and 50% KR groups, however, the percentage of goal-equivalent variability was much smaller. This finding was also reflected in the between-trial correlation between the finger forces. The ConFB group had a strong negative correlation, indicating that the trials were aligned along the direction of the line, \( F_R + F_L = 10 \) (i.e., the UCM direction along which variability does not affect performance), whereas the KR groups had a strong positive correlation, indicating that the trials were aligned along the direction of the line, \( F_R = F_L \) (i.e., the direction orthogonal to the UCM along which variability leads to error). In Experiment 2, the results were identical when the difference in the mean times-to-peak force between the ConFB and the KR group was reduced from 731 ms to 118 ms. The identical results suggest that the different strategies that the groups adopted were predominantly related to using the available visual information and not merely a consequence of differences in the times-to-peak force.

In a similar study that attempted to find differences in strategies, Mackrous and Proteau (2007) suggested that the poor performance of the ConFB group under no-KR was because of participants’ use of the same motor plan in transfer that they had used during acquisition. From the perspective of movement variability, the present study showed that the poor performance of the ConFB group was not associated with an increase in the amount of outcome variability or total movement variability during acquisition (both of these were smaller in the ConFB group compared with all the other groups), but rather with the high percentage of variability along the UCM (i.e., tending to use multiple solutions to achieve the goal). The inference that orienting

![Figure 7. CE x Time-to-Peak Force representation of the performance of each participant in the ConFB and 100% KR groups on the 2-min and 24-hr no-KR tests, respectively, in Experiment 2. The criterion performance was at (600, 0), CE = constant error; ConFB = concurrent feedback; KR = knowledge of results.](image-url)
the variability along the UCM is responsible for poor performance in this task is strengthened when considering the ConFB test information group. Participants in this group received identical visual feedback to the ConFB group but were aware of the upcoming no-KR test. This group tended to decrease the percentage of goal-equivalent variability during acquisition and performed better on the no-KR test compared with the ConFB group.

The other interesting aspect of the performance was that in the no-KR test, there was a switch in strategy from the acquisition blocks to the no-KR test for the ConFB group. The correlations between the finger forces at the time-of-peak force during the acquisition blocks were strongly negative but switched to being strongly positive during the no-KR test. In contrast, the KR groups showed little change in the correlation from the first block of acquisition to the no-KR test. These results support the idea that practicing with ConFB not only impairs an accurate representation of the task goal (as noted by the increase in CE in the no-KR test), but also possibly promotes using a coordination strategy that cannot be sustained when it is absent (Schmidt & Wulf, 1997).

Goal-Equivalent Variability Under ConFB

The reason for ConFB introducing this trial-to-trial variation can be explained by using the minimum intervention principle that Todorov and Jordan (2002) proposed. According to this principle, when feedback can be used to control the movement, the controller does not correct for variability in the individual degrees of freedom that do not affect task performance. For the ConFB group, the visual information about the instantaneous force can be used to correct only the variations that change the peak total force, allowing goal-equivalent variability. The influence of visual information during the pulse on goal-equivalent variability in this task is seen in Figure 6 in which the differences in strategies between the groups emerged only approximately 50% into the movement. In contrast, the 100% KR group, which did not have access to visual information when producing the pulse, maintained the same positive correlation between the fingers from pulse initiation until the time-of-peak force. This is also evident in the no-KR test in which none of the groups had visual information during the pulse and all groups showed a positive correlation strategy.

Although visually mediated feedback corrections during the pulse can give rise to negative correlations, negative correlations are not a necessary condition for accurate performance. This is because although decreasing error reduces the variance in the error dimension, the variance in the goal-equivalent direction is not related to performance. The variance in the goal-equivalent direction can be (a) greater (leading to negative correlation), (b) comparable (zero correlation), or (c) smaller (positive correlation) than that of the variance in the error dimension (Latash, Scholz, & Schöner, 2007). In this case, even though all groups reduced their errors with practice, the presence or absence of visual information during the movement was a primary influence on the actual strategy used.

A Nonoptimal Strategy?

The results also raise the following question: Why is positive correlation strategy preferred even though it is not the ideal strategy for producing constant force? We speculate that there are two possible reasons. First, because the ConFB group was primarily aligned along the UCM, participants did not receive any information about movement variability from the outcome score (which was always close to the criterion). In contrast, orienting the variability orthogonal to the UCM may be beneficial to learning because errors at the level of response execution (i.e., the individual degrees of freedom) were directly reflected as errors at the level of the task outcome. For example, if the task error is $xN$, a strategy with positive correlation between the fingers (i.e., $F_k = kF_L + c$, where $k$ is positive and $c$ is an arbitrary constant), allows a direct translation of the $xN$ of total error into an error of $kx(1+k)N$ for $F_k$, and $x(1+k)N$ for $F_L$. The analysis of the correlation between the error and the corrections supported this idea because we found a stronger correlation between the task error and the change in the individual finger forces in the ConFB test information, 100% KR, and 50% KR groups (which had positive $k$) than with the ConFB group (which had negative $k$). Being able to make this association between errors at the level of movement outcome and errors at the level of response programming has been considered an important component in learning (recall schema; Schmidt, 1975). In the present article, the positive correlation strategy seemed to facilitate the mapping between the task outcome and the individual degrees of freedom.

A second reason for adopting a positive correlation strategy may be related to the stability of the coordination pattern. A positive correlation strategy in which an increase or decrease in peak force in one finger is accompanied by a concomitant increase or decrease in peak force of the other finger, reflects a tendency to coordinate the fingers of the two hands into a single collective unit. This feature has been observed in several experiments on bimanual coordination (e.g., Kelso, Southard, & Goodman, 1979; Marteniuk, MacKenzie, & Baba, 1984). Therefore, the high stability of the positive correlation strategy may be a reason why it is preferred, even if it results in more error during acquisition and may explain the switch in strategy of the ConFB group during the no-KR test.

Delayed Tests and the Influence of Guessing

Although researchers often use delayed transfer and retention tests to evaluate the permanent changes in learning, it is worth noting that delayed tests can introduce factors such as guessing, which contribute to the change in performance. The effect of delayed tests has been considered in the context of educational testing, in which test scores are determined by content knowledge and the extent to which correct answers can be guessed (Johnson & Rosenthal,
In the present study, we found that participants in the ConFB group were guessing the force level on the delayed transfer test. Considering the influence of guessing may be particularly important in scaling tasks, guessing may occasionally lead to good performance. Consequently, there would be increased within-group variability and statistically nonsignificant results on the delayed transfer test, which could lead researchers to conclude that the effects observed were transient effects. In these cases, the analysis of within-group variability and different aspects of performance (such as measures related to timing or the coordination pattern) may be critical to examining the contribution of different factors to performance on delayed retention or transfer tests.

Covariation and Skill

Last, the results also raise an issue about the relation between covariation and skill. The ability to generate multiple solutions for achieving the same outcome has been considered a hallmark of skilled performance (Bernstein, 1967). More recently, compensation between motor elements (i.e., negative covariation) has been seen as an essential feature of motor synergies (Latash et al., 2002). Other studies have similarly shown that with practice, participants move to and align along solution spaces that are tolerant toward error in task performance (Kudo, Tsutsui, Ishikura, Ito, & Yamamoto, 2000; Müller & Sternad, 2004). However, the present study showed the following three important results: (a) ConFB induces negative covariation, but this is actually detrimental to performance when feedback is removed; (b) information about the no-KR test led to positive covariation even though ConFB was available; and (c) even after extensive practice, the KR groups did not show negative covariation, although these two groups had the best performance on the no-KR test. In this regard, the role of covariation in learning needs to be explored in terms of not only optimizing task performance, but also considering the stability of coordination patterns. A nonoptimal region in terms of task performance may be preferred even after extensive practice if the coordination pattern underlying the performance is highly stable.

Although the feedback information to optimize learning of a given task could be dependent on task constraints (e.g., the shape of the force pulse to be used; Newell & Carlton, 1987), the present study provided support for the idea that ConFB is detrimental to performance in a no-KR situation because it disrupts movement consistency. Though ConFB was associated with the least amount of outcome and movement variability during acquisition, a high percentage of the variability was goal-equivalent (i.e., participants used different solutions from trial to trial to achieve the same goal). It is probable that using different solutions from trial to trial may be part of maladaptive corrections (Schmidt, 1991) that hinder the formation of a stable coordination strategy during acquisition, which in turn results in poor performance when feedback is removed.

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NOTES

1. The Mahalanobis distance is a distance measure that takes into account the covariation between the variables (unlike Euclidean distance). For a multivariate distribution with mean μ and covariance C, the Mahalanobis distance of an observation x from the mean is given by: D = [(x - μ)T C⁻¹(x - μ)]^1/2

2. Although a solution is possible even for negative correlations (−1 ≤ k ≤ 0), negative k would involve (a) a correction at one finger that is greater than the total error itself and (b) corrections in different directions for both fingers (i.e., one finger would have to produce more force and the other would have to produce less force than what they did respectively on the previous trial).

REFERENCES


